

Geomorphology and Holocene history of the tidal flats, King Sound, north-western Australia

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Abstract

King Sound in north-western Australia, with a tropical semi-arid climate, is situated in a tide-dominated regime. The shores of King Sound are bordered by wide tidal flats that exhibit a considerable variation in geomorphology and stratigraphy. The stratigraphic sequence has developed as a result of tidal flat accretion during 3 Quaternary (2 Pleistocene, 1 Holocene) transgressions; this has built a shore-fringing sediment platform or wedge upon which modern geomorphic processes act. Erosion is the dominant and net geomorphic process forming the tidal flats today. Three types of erosion—sheet, cliff and tidal creek—are important. The local geomorphology of tidal flats is an expression of which erosion type is dominant and the regional geomorphology is largely an expression of the extent that erosion has removed Holocene, Pleistocene and bedrock stratigraphic units. Determination of erosion rates over the past few decades, extrapolation of these rates into the past, together with stratigraphic and diagenetic data point to a long-term erosional history for King Sound. However, sedimentation occurred earlier in the Holocene, when a more humid climate provided a large river runoff and sediment input, and tidal flat sediments built up an extensive coastal plain. Since about 5000 years BP conditions have become more arid and the Holocene deposits have been trimmed back or totally removed. This has continued up to the present, with erosion today the dominant shore-forming process.

Introduction

This paper reports the results of an investigation on the tidal flats of King Sound (Fig. 1) which are undergoing widespread regional erosion. The area is situated in the tropical north-west of Australia along a coastline with a large tidal range. The shores of King Sound are bordered by tidal flats that exhibit a considerable variation in geomorphology and stratigraphy. Previous studies have shown that sediments which comprise this tidal flat wedge (or platform) have accumulated during 3 Quaternary marine transgressions (2 Pleistocene and 1 Holocene; Semeniuk 1980). However, studies of modern processes, rates of erosion, geomorphology and stratigraphy of the tidal flats show that the modern King Sound morphology has formed largely by erosion. The range of shoreline types is merely the expression of age and extent of erosion as well as type of underlying stratigraphy. The Holocene history of King Sound is preserved in lithofacies of Holocene formations, in gravel lags across King Sound and in diagenetic overprints on the Quaternary formations. Within these features is recorded a history of Holocene deposition, climatic change, erosion, evolution of groundwater chemistry and progressive change in geomorphology.

Methods

The King Sound tidal flats were studied during 1973-1977. Tidal flats were surveyed along transects (Fig. 2) and related to tide levels and

Australian Height Datum (AHD). Eighty two field stations were set up along the transects and at numerous other localities, to document geomorphology, stratigraphy and biotic communities, and to collect samples of sediment, groundwater and biota.

Stratigraphy was investigated by hand augering (to 5 m depth), vibrocoring to extract intact core (to 7 m depth) and augering with Gemco rig (to 16 m depth). Stratigraphic relationships are well exposed for direct observation and measurement on deeply incised tidal creek walls, cliff lines and across vast erosion surfaces from which the modern sedimentary veneer has been stripped (Semeniuk, 1980).

The relative importance of erosion over sedimentation was assessed (a) by using vertical aerial photographs taken in 1949, 1967, 1974 and 1977, (b) by oblique aerial photographs taken annually of key areas during 1972-6 and (c) by observation and experiments in the field. On the ground, processes of erosion and sedimentation were observed and were documented as they took place. The products of erosion and sedimentation were also documented locally at field stations and regionally by mapping along the coastline and creeks. Rates of erosion and sedimentation were calculated from (a) measurements taken directly against fixed datum points such as stable markers (10 in total) or iron pegs (16 in total), (b) measurements taken from aerial photographs and (c) measurement of an

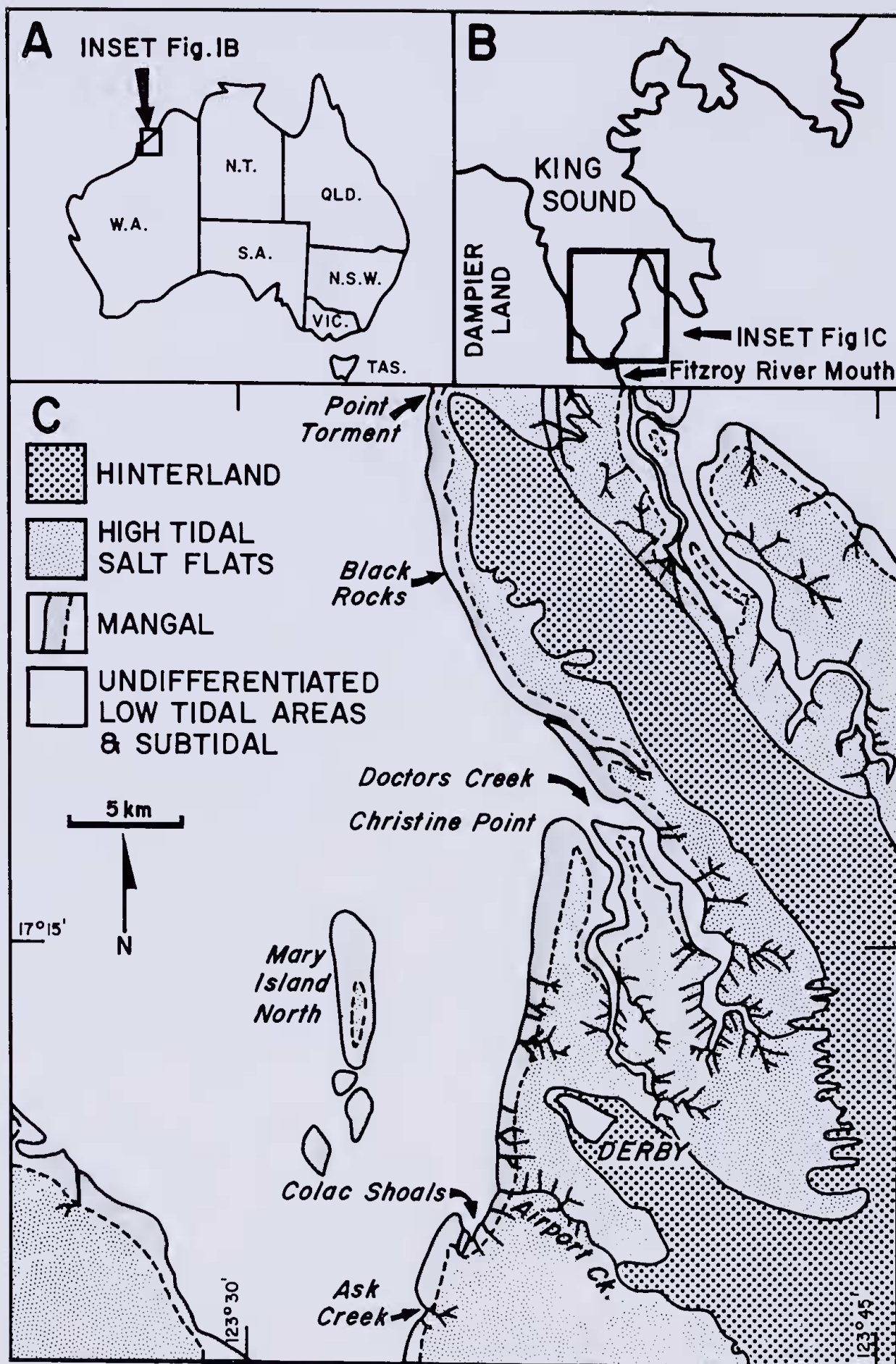


Figure 1.—Map showing location of study area within King Sound along the north-western coast of Australia. Figure 1C shows broad geomorphic units of the tidal flats and key geomorphic localities mentioned in text.

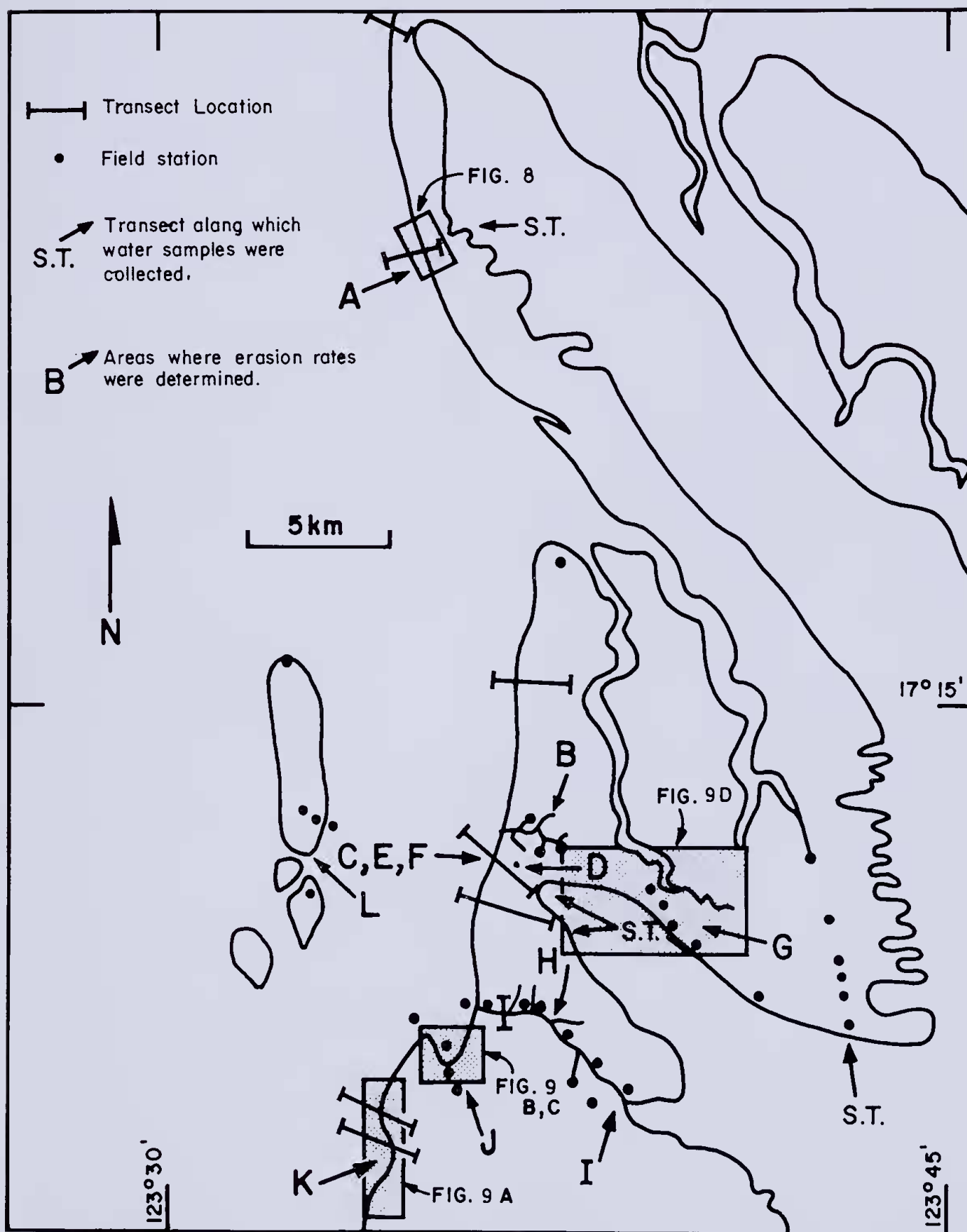


Figure 2.—Map showing location of various transects, field stations and erosion study areas. Insets are illustrated in more detail in Figures 8 and 9.

erosional scour against a feature of known age (e.g. mangrove roots). Field measurements were made during 1974-1977 on a 6-12 monthly basis. The areas used for determination of rates of erosion by aerial photos and by ground measurement are indicated on Figure 2.

The physical oceanography of King Sound in terms of circulation, tidal currents, waves and wind set is largely unknown in detail. It was necessary therefore to make observations and measurements particularly on tidal currents and waves at selected localities and at various times to assess their range of values. While these results are not exhaustive they give some idea of the magnitude of oceanographic features in the embayment. Tidal currents were measured in several localities to check routinely the magnitude of flow. Floating markers were released and their travel timed to determine surface current velocity both in open waters (7 markers) and in tidal creeks (25 markers). Heights of waves generated by sea breezes were estimated by rise and fall of water level against a calibrated tide pole.

Regional setting

Physiography and geology

King Sound, a large shallow (6-18 m deep), marine embayment of approximately 5000 km² is located in the Kimberley region of north Western Australia. During the wet season King Sound is the estuary of the Fitzroy River (Fig. 1); during the dry season King Sound essentially is a marine embayment. Geologically, King Sound is a Quaternary depositional embayment within the Canning Basin. To the north King Sound is flanked by a hinterland of pre-Quaternary (Proterozoic to Tertiary) rocks and vegetated Quaternary red sand dunes; there are rocky coastlines and narrow tidal flats (Casey 1958; Gellatly and Sofoulis 1973).

To the south the shore is composed of Quaternary sedimentary materials, such as vegetated red sand dunes, grassy alluvial plains and broad tidal flats (Fig. 1); these Quaternary sediments overlie, at shallow depths, Mesozoic rock and Tertiary ironstone (Casey 1958). The main King Sound embayment, as delineated by mangroves that occur at about mean sea level, is funnel-shaped narrowing to the south toward the Fitzroy River. However, its shape at the high spring tide mark tends to be more irregular to sub-rectangular.

The main area of study was the southern portion of the east shore of King Sound where tidal flats are broad and mangroves well-developed. In these locations the tidal flats can be zoned into several units based on geomorphology and distinct vegetation communities.

Climate

Commonwealth Bureau of Meteorology (1975) data show that Derby has a semi-arid, tropical climate of monsoonal character (Bshw type of Köppen 1936). Approximately 620 mm of rain falls in a short wet period in summer between December and March. During winter there is negligible precipitation. The annual evaporation is approximately 3600 mm (class A pan or 2400 mm, sunken pan). Air temperatures are relatively high for both the wet and dry season (maximum commonly 33-39°C and 30-34°C respectively).

Wind data for 0900 hrs and 1500 hrs over 4 years analysed by Jennings (1975) show there are 2 wind seasons corresponding to the wet and dry seasons. Winds in general are light, with speeds mostly < 4.5 m/s. Only 13% of wind in the dry season have speed > 4.5 m/s and 17% of winds are > 4.5 m/s in the wet season (Jennings 1975).

In the dry season Trade winds from east and south-east are dominant in strength and frequency; an afternoon seabreeze is developed from north-west and west. During the wet season wind from north-west and west are dominant in frequency and seabreezes are subordinate. The wet season is also the period of tropical cyclones. Analysis of cyclone tracks over a 60 year period shows that a cyclone passes within 100 km of Derby approximately every 2 years, while one passes within 50 km of Derby every 5 or 6 years (Coleman 1971).

The importance of wind for the study area is the generation of waves. Seabreezes (during the dry season) and north-westerly to northerly winds (during the wet season) are responsible for generating small waves (generally < 0.5 m in height).

Physical oceanography

The coastline of King Sound has large semidiurnal tides (Easton 1970). Equinoctial spring tide range recorded at Derby is up to 11.5 m; the mean spring tide range is about 9.4 m; the mean neap range is 4.5 m (Australian National Tide Table 1979). Abbreviations for tidal levels used throughout this paper are:

EHWS = equinoctial high water spring
MHWS = mean high water spring
MHWN = mean high water neap
MSL = mean sealevel
MLWN = mean low water neap
MLWS = mean low water spring
ELWS = equinoctial low water spring.

Tidal currents reach velocities of 1.5-2 m/s in open waters, and 3 m/s (and greater) in narrow tidal creeks during periods of ebbing spring tide. During spring tides flood tidal waters traverse high tidal (salt) flats with velocity of up to 0.1 m/s. Ebbing tidal water draining along shallow creeks on high tidal flats may reach a velocity of 0.5 m/s.

Wave action overall is negligible. The embayment is protected from oceanic swell by islands of the Buccaneer Archipelago. However small waves are generated for a short period by afternoon seabreezes and by periodic summer storms. The waves are responsible for local coastline erosion and some shoreward transport of sand and debris. In the main, however, the embayment may be viewed as tide dominated.

During the wet season a combination of high (astronomical) tides, wind set (from north-westerly and northerly winds) and outflow of water from the flooding Fitzroy River creates a higher than normal regional water level. These are locally termed "king tides".

Surface and groundwater

The surface salinity of open water is 32-35‰. During spring tides tidal creeks that drain salt flats may have salinities above normal, up to 40-50‰.

The depth and chemistry of ground-water changes to landward with distance from the mangal. The water table is within 30 cm of the surface in the mangal; it may lie 2-3 m below the salt flat surface 4-10 km from the mangal (Fig. 3). Ground-water salinity at the seaward edge of the mangal is essentially that of seawater but it increases to landward gradually up to a maximum recorded value of 240‰ (Fig. 3D, E, F). These data show that groundwater is at concentrations where it is carbonate-precipitating and gypsum-precipitating (Clark 1924; Posnjak 1940). Under the more saline high tidal flats there are halite crystals (within 10 cm of the surface) as well as gypsum crystals and

weakly indurated carbonate nodules in the shallow subsurface (0.1-3 m).

The waters of King Sound and creeks that drain high tidal flats are turbid throughout the year. Turbidity is especially marked during spring tides. Water samples from selected transects across tidal creeks and the main embayment of King Sound have up to 1-2% (by weight) of mud in suspension. Since the Fitzroy River ceases flow after the wet season the turbidity cannot be attributed to river input. Rather it reflects the continual tidal flat erosion. Aerial observation show that these turbid waters extend out of King Sound as a plume. The suspended muds most likely are deposited far offshore out of King Sound in deep water.

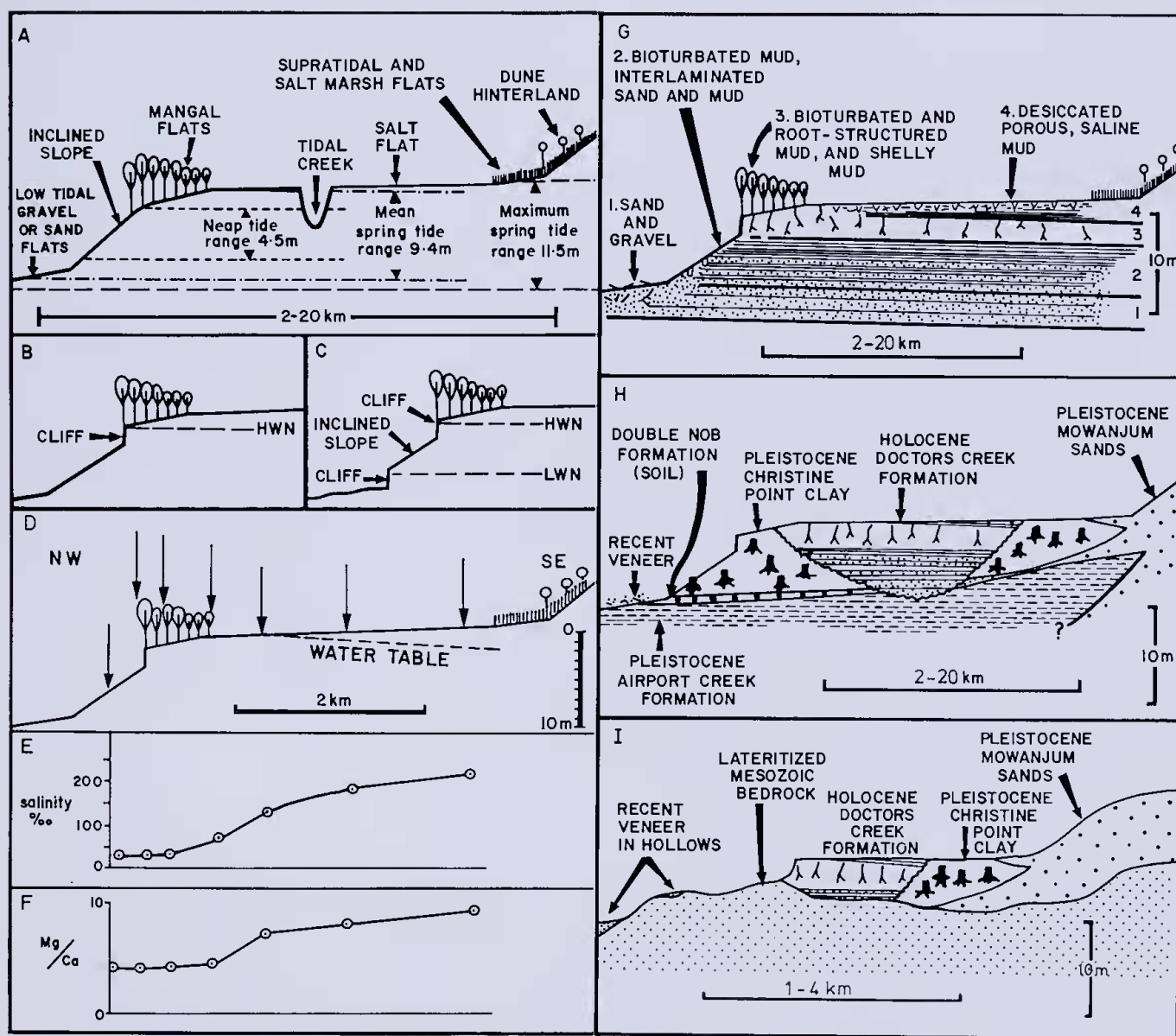


Figure 3.—A.—The full sequence of geomorphic/vegetation units; this profile is based on a transect from Derby (Fig. 1) but it is representative of profiles throughout the area. B and C.—Variation on the basic profile with sea cliffs developed at levels of HWN and LWN. D.—Profile across tidal flat in a traverse from Derby (see Fig. 1) showing geomorphic profile and position of water table. Location of stations (auger holes for water samples) are arrowed. Data collected 15 September 1974 and are representative of other traverses made on the flats. E.—Salinity of water samples collected from the field stations shown above. F.—Variation in Mg/Ca in water samples from field stations shown above. G.—Characteristics and distribution of the 4 surface sediment types on the modern tidal flat. The section under the tidal flat illustrates the ideal stratigraphy which develops with an accreting coastline. H.—Profile illustrating the actual stratigraphy that underlies the tidal flats in southern areas. Summary of lithology of each stratigraphic unit is given in Table 2. I.—Profile illustrating the actual stratigraphy underlying tidal flats in northern parts of the study area. Erosion has stripped away tidal flat and dune sediments, exposing underlying rock, and has cut out some geomorphic and stratigraphic units. Spits and cheniers are present where erosion has cut into dunes.

Table 1

Chemistry and Mg/Ca ratio of groundwater samples from selected localities

Sample No.	Sample location	Ions (mg/L)				Mg/Ca %
		Cl	SO ₄	Ca	Mg	
13	Middle salt flat transect 3	103 000	14 150	1 020	8 500	13.74
16	Seaward edge salt flat transect 3	19 100	2 650	470	1 310	4.59
30	Landward edge salt flat transect 4	120 000	10 950	1 220	6 750	9.13
32	Middle salt flat transect 4	107 250	10 450	....	....	....
23	Seaward edge salt flat transect 4	81 900	7 800	1 140	5 320	7.70
20	Landward edge of mangal transect 4	23 050	3 150	600	1 550	4.26
33	Seawater transect 4	19 850	2 600	470	1 270	4.46
011E	Middle salt flat, transect 5	132 400	11 300	1 065	3 825	5.93
011D	Seaward edge salt flat transect 6	67 350	7 250	1 200	1 960	2.69

Stratigraphy

Much of the surface of the tidal flat is cut into Pleistocene units, and less commonly into Tertiary laterite and Mesozoic rock. Accordingly the tidal flat surfaces in essence are unconformity surfaces. Six Quaternary formations are recognised underlying the tidal flats and onshore hinterland of the King Sound area (Semeniuk 1980). They are: (6) Point Torment Sand, (5) Doctors Creek Formation, (4) Christine Point Clay, (3) Double Nob Formation, (2) Airport Creek Formation and (1) Mowanjum Sand. The stratigraphic relationship between these formations is illustrated in Figure 3G, H and I, and their lithology is summarised in Table 2.

The Mowanjum Sand is the oldest Quaternary unit in the area; it rests unconformably on lateritized Mesozoic rocks, underlies the Airport Creek Formation and extends as tongues across the unconformity interfaces that separate the other Quaternary units. The Airport Creek Formation, the oldest Pleistocene marine unit in the area, is composed of semilithified to indurated laminites and beds of sand and mud. It is overlain by a thin palaeosol termed the Double Nob Formation which is overlain by the Christine Point Clay (4-6 m thick), a Pleistocene mangrove sediment unit. The Doctors Creek Formation (10-12 m thick), which is a Holocene shoaling tidal-flat sequence of sand, sand/mud laminite and bioturbated mud, unconformably

overlies the Christine Point Clay and occurs in large-scale scours cut into the underlying formation. The youngest formation, the Point Torment Sand, is a Holocene sequence of shoreline sandy spits. It overlies and interfingers with the Doctors Creek Formation and the modern veneers.

An ephemeral thin blanket of sediment covers much of the unconformity surfaces of the modern tidal flats is termed the Modern Veneer. The veneer on low to mid tidal areas is stripped frequently on a monthly or seasonal basis by spring tides or storms. Shallow excavations or augering distinguishes Modern Veneer from the lithologically similar Doctors Creek Formation.

Geomorphic units

The tidal flats and adjoining physiographic entities of King Sound are readily divisible into 12 geomorphic units (Fig. 3A, B C). These units are: (1) Vegetated dunes, (2) Supratidal and saltmarsh flats, (3) Salt flats, (4) Mangal flats, (5) Inclined slope, (6) Shoals, (7) Sand flats, (8) Gravel pavements, (9) Spits and cheniers, (10) Rocky outcrop, (11) Tidal creeks and (12) Sea cliffs. Many of these units are restricted to specific tidal levels but some (shoals, gravel pavements and rocky shores) occur across several tidal levels. Subtidal features are not subdivided nor considered further here.

Table 2

*Summary of lithology of stratigraphic units **

Stratigraphic unit	Age	Lithology	Remarks
Point Torment Sand	(Youngest) Holocene	Cross-laminated, cross-bedded and locally bioturbated quartz skeletal sand; locally shelly and lithoclastic	Shoreline sand spits and cheniers derived by erosion of Mowanjum Sand
Doctors Creek Formation	(Older) Holocene	Top—laminated mud, bioturbated mud mud/sand laminate Base—sand and shelly sand	Shoaling sequence of tidal-flat sediments
Christine Point Clay	Pleistocene	Bioturbated and root-structured slate grey mud with in situ large mangrove stumps	Tidal-flat unit deposited with sea level 1.5 m below present
Double Nob Formation	Pleistocene	Homogeneous, grey muddy sand with granule-sized pedogenic nodules	Nodular soil similar to those forming today under inland black soil savannah plains
Airport Creek Formation	Pleistocene	Interlayered, laminated and cross-laminated sand, silt and clay; semi-indurated by calcite cement	Tidal-flat unit irregularly cemented into nodules
Mowanjum Sand	Pleistocene	Red to orange quartz sand; homogenous, root-structured to mottled	Oldest Quaternary unit, aeolian in origin

* Data from Semeniuk 1980.

Vegetated dunes.—All types of tidal flat are bordered by a hinterland of red sand dunes (Fig. 1). These longitudinal dunes, with up to 5 m relief above highest astronomical tide, are fixed by *Eucalyptus* and *Acacia* "pindan" shrub (Stewart *et al.* 1960). They impinge onto and extend as fingers beneath the tidal flat sediments (Jennings 1975; Semeniuk 1980).

Supratidal and saltmarsh flats.—These are gently sloping surfaces (up to 200 m wide, gradients 1:100) underlain by mud or muddy sand that border the hinterland. The higher parts of the flats, vegetated by terrestrial grasses and other low-growing angiosperms, are above EHWS; the lower parts, vegetated by samphires, are inundated by EHWS tides.

Salt flat.—The salt flat is vegetation-free, sub-horizontal with gradient of $\leq 1:2000$ and up to 50 km² in area. It is flooded by tides higher than MHWS. The surface mostly is firm, desiccated saline mud with burrowing crabs, worms and insects at its more seaward portions. Groundwater hypersalinity precludes biota over most of the flat.

Mangal flat.—This is a vegetated flat tens of metres to over 1.5 km wide with gradients of 1:600 to 1:25 that occurs from about MSL to MHWS. It is vegetated mainly by mangroves (mangrove community = mangal: terminology of McNae 1968); samphires occur toward landward portions. The surface is underlain by mud, shelly mud and sandy mud bioturbated by plants and animals.

Inclined slope.—This surface is a vegetation-free slope, 100–200 m wide, with gradients of 1:20 to 1:40, between LWN to MSL (or HWN). It is underlain by thixotropic muds or interlayered mud and sand or Pleistocene units (Fig 8B of Semeniuk 1980) and is inundated by all tides.

Shoals.—Shoals are developed within the main King Sound embayment. They are large-scale hummocky units with an area of several square kilometres; channels and washaways are common. Shoals range in relative height from subtidal to generally above MSL. Some shoals are capped by mangroves and have built up to above HWN.

Sand flats.—Sand flats are typically low tidal sub-horizontal surfaces and are up to 1 km² in area. They are rippled, megarippled and plane-bed sand sheets (Fig. 4C) that have local shell and rock gravel veneers on the surface.

Gravel pavements.—These are subhorizontal to gently inclined surfaces up to several square kilometres in area that are subtidal or only exposed by LWS tides. The surface is littered by platy gravel derived from shallow subcropping Airport Creek Formation. Locally small knolls of outcrop < 1 m high protrude through the gravel veneer. In some localities the gravel pavements are reworked into megaripples (Fig. 4A, B).

Spits and cheniers.—These are narrow shoreline sand accumulations. They form single spits, or may be stacked, or may form a chenier plain. Individual spits are up to 1.5 km long; width varies from a few metres to over 20 m. Splays may span a total width of 200 m. Subaerially and tidally degraded spits are < 1 m high.

The spits and cheniers occur from HWS up to, and above, EHWS. Within tidal ranges the units are

vegetation free, but above EHWS they are vegetated by *Spinifex lirsutus* and *Acacia*.

Rocky outcrop.—Lateritized sandstone and other pre-Quaternary rock locally crop out either as a headland or a knoll. These may extend from supratidal to subtidal, but outcrop may be restricted to a narrow range of the tidal zone.

Tidal creeks.—Tidal creeks range from small ruts and gullies, < 1 m deep and wide, to > 10 m deep and 1 km wide. Creeks in plan are meandering, ramifying and bifurcating, but are not laterally migrating because they are entrenched. Small tidal creeks and gullies are commonly V-shaped in cross section; larger systems are characteristically a broad U-shape. Tidal creeks incise all but highest tidal and supratidal units.

Sea cliffs.—Sea cliffs occur continuously along most of the tidal zone of King Sound and are developed at many tidal levels (Fig. 5) although more usually they are developed at 2 levels: the more common is immediately in front of the mangal flat (Fig. 5C); the other is at LWN level (Fig. 5D). Cliffs are 1–2 m high; rarely they are up to 6 m high. The retreating toe of a sea cliff often is marked by debris reworked from the eroded formation. The debris includes: (a) mangrove wood fragments, (b) mud-ball conglomerates, (c) blocks of mud, (d) lithoclast pebble conglomerate (carbonate nodules reworked from Airport Creek Formation) and (e) wedges and sheets of granule deposits (carbonate nodules reworked from Double Nob Formation).

Types of tidal flats

The tidal flats of King Sound are varied in morphology and stratigraphy. Six main types of tidal flat occur and each type consists of a different combination of geomorphic units. The tidal flat types are: (1) Depositional flats, (2) Unconformity flats, (3) Shoal flats, (4) Spit and chenier flats, (5) Rocky shores and (6) Channelled flats. These types of flats with their component geomorphic units are diagrammatically illustrated in Figure 6.

Depositional flats (Fig 6).—This type of tidal flat occurs in restricted areas where deposition of sediment is taking place or where there is a state of equilibrium between sedimentation and erosion. The geomorphic units on this type of tidal flat include: a broad salt flat followed to seaward by a wide mangal flat, then an inclined slope and low tidal sand flats; there is a gradual unbroken slope from high tide through to low tide; the inclined slope is underlain by interlayered mud and sand to some depth and ultimately low-tidal sand underlies most of the flat. A characteristic feature is the general absence of cliffs and lack of subcropping or shallowly buried Pleistocene formation.

Unconformity flats (Fig. 6 and 7B).—This type of tidal flat is most common south of Doctors Creek (Fig. 1). It is essentially similar in morphology to the depositional tidal flats except for the following features: (a) Seacliffs are developed at levels of HWN and LWN and (b) Pleistocene sediments form the tidal flat surface on the inclined slope (i.e. Christine Point Clay with protruding fossil mangrove stumps) and low tidal flats (i.e. outcrops of Airport Creek Formations or gravel pavements). Doctors Creek Formation locally may form the foundation material,

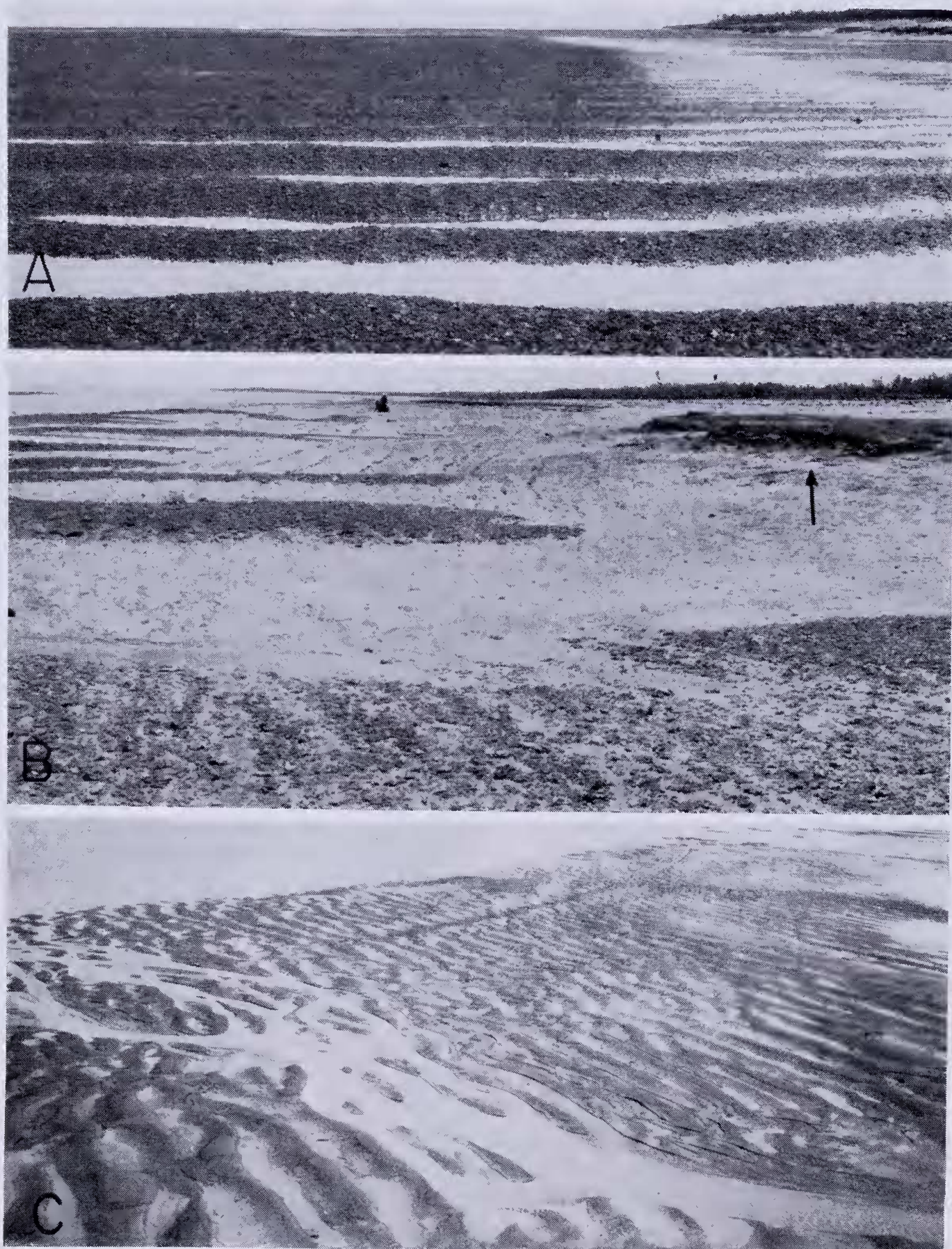


Figure 4.—Low tidal flats. A.—Gravel pavement exposed by low spring tide. Gravel here has been formed into megaripples oriented normal to the coast. B.—Patchy distribution of gravel veneer on exposed Pleistocene Airport Creek Formation. Arrow points to outcrops of Pleistocene nodular soil (Double Nob Formation). C.—Megarippled sand flat exposed by low spring tide.

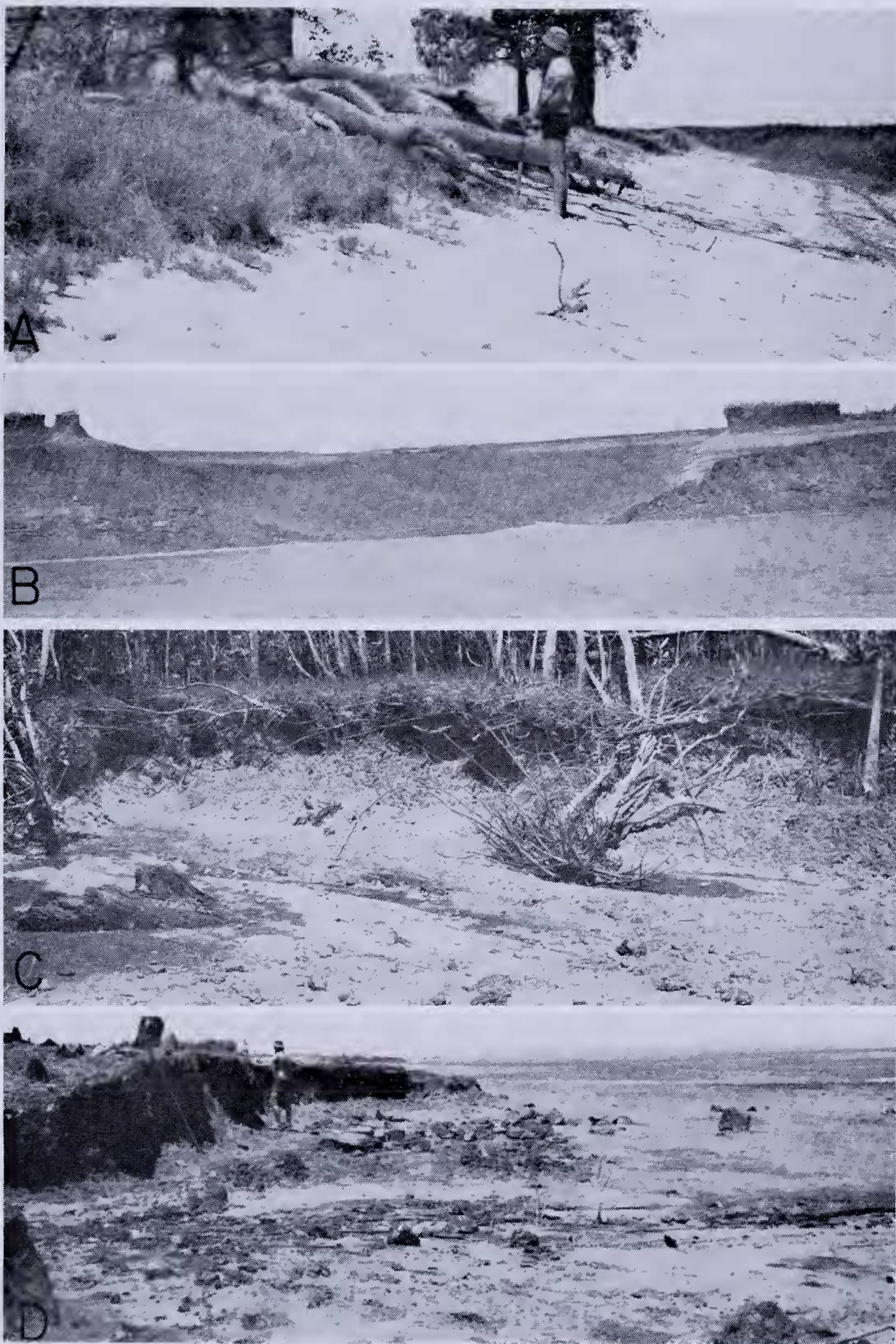


Figure 5.—Seacliffs cut at various tidal levels. A.—Cliff cut into hinterland dune terrain. Mangroves are on right. The steeply inclined sandy surface encompasses the interval between MHWS and EHWS. Erosion has incised into the grassy plain to the left and here has exposed roots of the Boab tree. During the 1940s the cliff was some 6 m further to seaward from this tree (H. Bromby, pers. comm.). B.—Cliff cut into salt flat. Evident here are hanging valleys of a truncated high tidal creek system. C.—Cliff (1 m high) cut at level of HWN into the seaward edge of the mangal flat. Mangrove roots are exposed and mangrove trees are in various stages of collapse. Note gravel developing at toe of cliff. D.—Cliff cut at level of LWN into the inclined slope. Note gravel developing at toe of cliff.

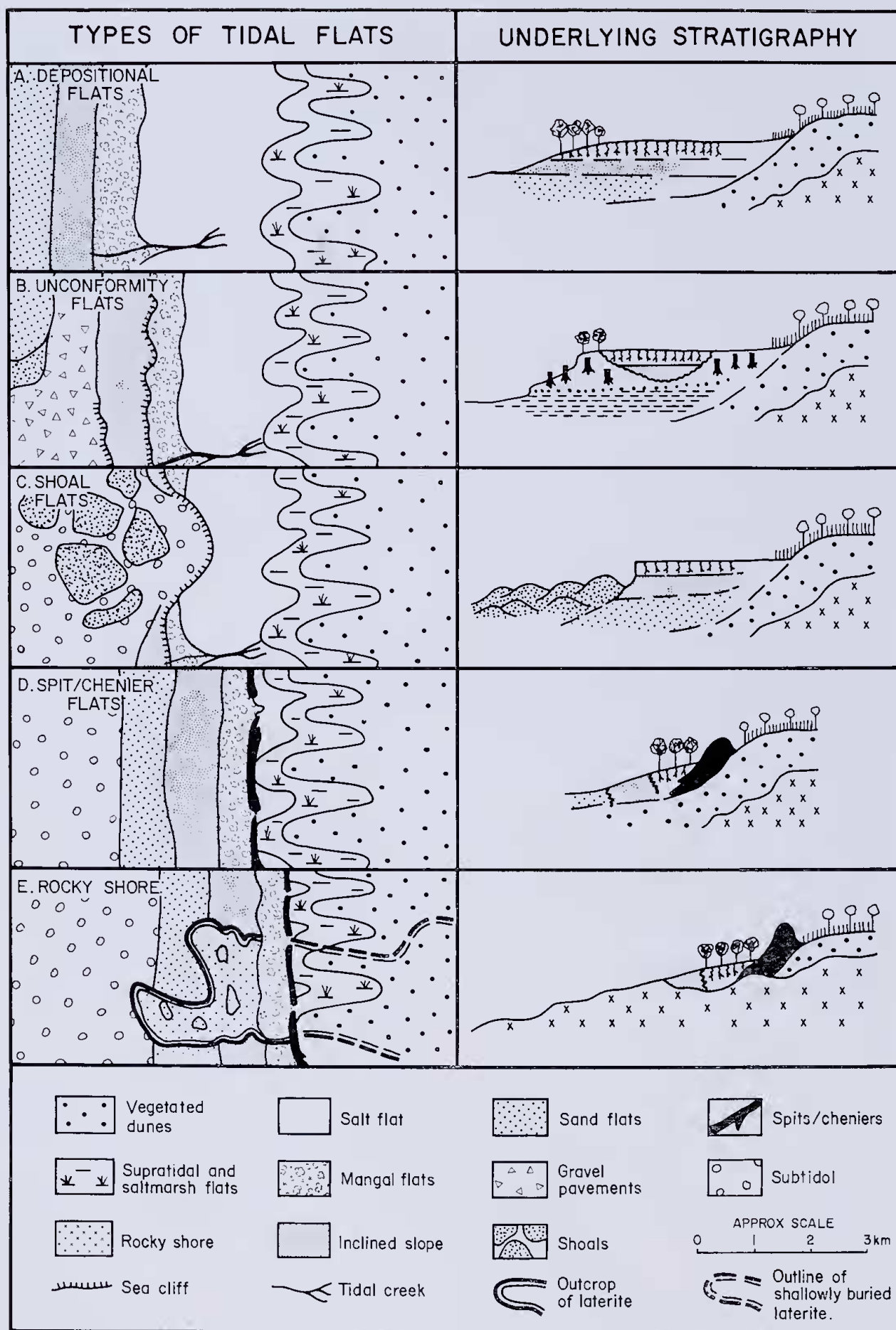


Figure 6.—Diagram illustrating various types of tidal flats, their component geomorphic elements and the typical underlying stratigraphy. Key to stratigraphic units is shown in Figure 3G, H, and I.



Figure 7.—Aerial view of various types of tidal flats. A.—Spit/chenier flats and locally rocky shore (arrowed). The eroding line marked by spits cut into the tips of dunes is evident here. B.—Unconformity flats. Note the wide salt flat, the narrow mangal flats which are flanked to seaward by an inclined slope. The seaward margin of the inclined slope is marked by the broken line. Arrows labelled 1 point to gravel pavements; arrow 2 points to sand flats that overlie gravel. C.—Shoal flats. Portion of this shoal system is capped by mangroves.

Shoal flats (Figs. 6 and 7C).—These flats are characterised by shoals in subtidal to mid-tidal areas. Shoals are abundant in the southern parts of the King Sound embayment where they effectively choke the estuary of the Fitzroy River. Shoal tidal flats also occur against rapidly eroding shorelines cut into Doctors Creek Formation (Fig. 6). In both cases they occur offshore from the main tidal flat that flanks the hinterland.

Spit and chenier flats (Figs 6 and 7A).—These flats are so named because they contain spits and

cheniers as important components; otherwise they are similar in mid-tidal to subtidal portions to unconformity and depositional tidal flats. The mid to low tidal parts are gravel pavements, sand flats, inclined slope (underlain by contemporary sediments or shallowly buried Pleistocene Christine Point Clay) and mangal flats. Mangal flats however, abut either supratidal flats, or vegetated red sand dunes, or spits and cheniers (Fig. 8). In many areas mangal flats are invaded by spits and cheniers. Salt flats, if present, are narrow or occur in corridors between longi-

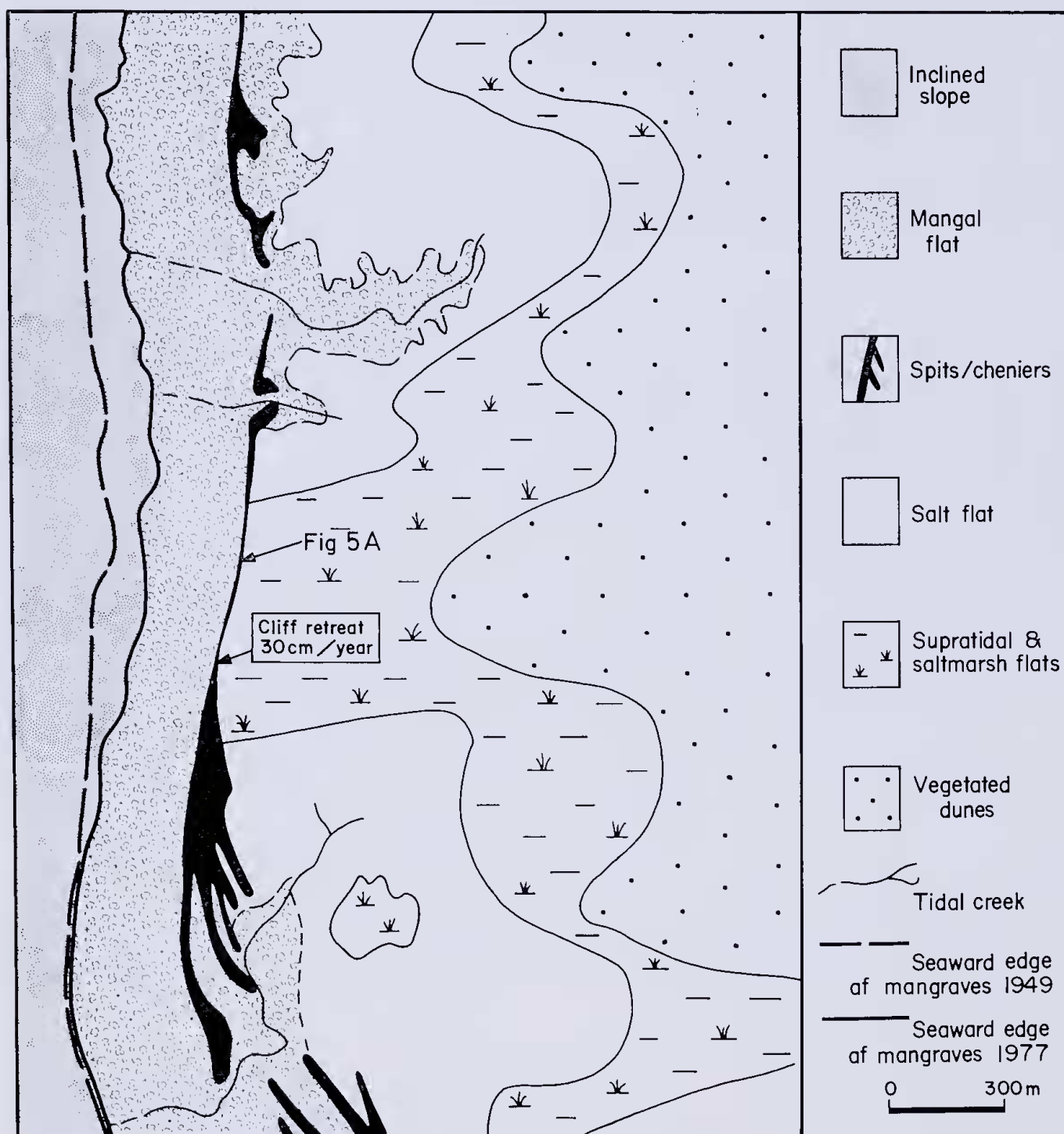


Figure 8.—Map showing distribution of geomorphic elements in a spit/chenier flat. Note the relationship of spit/cheniers to the eroding tip of a longitudinal dune. Erosion is evidenced by the retreat of the mangrove, the measured retreat of the high tidal cliff and the exposed roots of the boab tree (see Figure 5A).

tudinal dune fingers (Fig. 8). Spit and chenier flats are abundant north of Doctors Creek (Fig. 1).

Rocky shores (Figs. 6 and 7A).—This type of tidal zone is developed where there is rocky outcrop. Outcrops may extend across the full tidal range. More usually outcrops form distinct knolls that protrude above surrounding Quaternary sediments and so form "reefs" or headlands of limited extent. Local pockets of sediments occur in depressions in the rocky shores and the sediment type is typical of the tidal level at which it occurs e.g. low tidal depressions are filled with sand, mid-low tidal depressions are filled with sand/mud laminites. Rocky shores are more common in the far northern parts of King Sound, north of the study area depicted in Figure 1B.

Channelled flats.—All tidal flats and all types of stratigraphic profiles are incised by tidal creeks to varying extent but, where tidal flats are abundantly incised, the tidal zone becomes merely a complex of channels. Here, the integrity of the various tidal flats described above, becomes subordinate to channels. Channelled flats are distributed in discreet areas along the coast (Fig. 1C). The stage to which a flat is incised to be termed channelled flat is arbitrary, since every gradation from one extreme to the other occurs. For purposes of this paper, creek systems as large as, and larger than Airport Creek are termed channelled flats. Since creeks deepen, widen and lengthen in time the relative age of a creek can be inferred. The sequence Ask Creek, Airport Creek, Doctors Creek probably represent an age sequence from youngest to oldest (Fig. 1C). Within the larger channel systems sediment remobilisation and redistribution has resulted in development of large mid-channel shoals, point bar deposits and creek mouth fans.

Surface processes

Erosion and local sedimentation are taking place concurrently along some parts of the King Sound coastline and are alternating along other parts. However, erosion today is the obvious and dominant process and from a review of aerial photographs spanning 28 years it is also obvious that it is the net process (Jennings 1975; Semeniuk 1980).

A study of stratigraphy also leads to this conclusion. Modern tidal flat sediment can be categorized into 4 suites correlated to geomorphic units (Fig. 3G). Low tide areas are underlain by sand shaped into megaripples and ripples. Inclined slopes are underlain by interlaminated sand and mud passing upslope into laminated mud. Sediment under mangroves is root-structured mud, sandy mud or shelly mud, thoroughly mixed by animals and plants. Salt flat sediments are vesicular and laminated mud; during periods of long exposure on high-tide parts of flats, there is growth of evaporite minerals such as halite and gypsum. With coastal accretion, these 4 suites would migrate to seaward, to build a shoaling stratigraphy (Fig. 3G).

On the tidal flats however the 4 sediment types usually form a thin sheet (modern veneer) that blankets a contrasting underlying stratigraphy (Semeniuk 1980). Where the veneer is stripped by spring-tide currents or storms, the underlying sediments exposed may bear no relationship to the modern sediment normally found in that environment (Figs. 3H, I; 4A, B; and Fig. 8B of Semeniuk 1980). For

most of the tidal flats therefore, there is a major discrepancy between surface sediments and the underlying stratigraphy, indicating that the coastline did not accrete by shoaling or progradation of recent sediments, but rather that the coast is undergoing net erosion.

Deposition of sediment does take place locally and during specific times, but it is overall negligible. The predicted shoaling stratigraphy (Fig. 3G) is present in two types of settings: (a) in large-scale hollows or scours which at present are not depositional and appear to be former embayments (Semeniuk 1980) and (b) in small embayments where deposition is taking place locally.

Types of erosion

Erosion is the principal process shaping the modern geomorphic surface in southern King Sound. It is occurring at all tidal levels and is reflected in numerous small-and large-scale geomorphic features depending on location, type of substrate, substrate cohesion, intensity of current flow, slope of surface, and many other factors. Three types of erosion appear to bear directly on the development of geomorphology; these are sheet, cliff and tidal-creek erosion. They occur to some extent at all localities but the geomorphology is determined by those which are dominant.

Sheet erosion.—Sheet erosion strips away extensive sheets of sediment at all tidal levels. It is an important erosive process, because it involves large expanses of the tidal flat which are progressively lowered a few millimetres at a time. Sheet erosion occurs most readily on salt flats that have dried out during neap tides. During this period the mud becomes vesicular as gas bubbles coming from shallow depths are trapped by a cohesive drying surface layer. Worms, insects and crustaceans burrow into the mud, producing innumerable small tunnel systems and desiccation results in shrinkage cracks aligned both parallel to and perpendicular to the surface. During prolonged exposure, soil moisture evaporates and salt crystals grow into mud-disrupting aggregates. A spring tide returning after 2-4 weeks rapidly traverses this indurated mud pavement virtually picking up no sediment. With inundation water fills cavities in the mud and the salt dissolves ceasing to support the surrounding mud which collapses. Thus, the mud quickly becomes a thick suspension and the substrate which did not easily yield to tidal scour on the flooding tide, now readily erodes. The topmost layer is removed and the ebb tide carries abundant mud particles in suspension out to sea.

Sheet erosion is evident on mangal flats where mangrove roots are progressively exposed. It occurs on the inclined slope in front of mangroves as evidenced by both erosional scours and the seasonal stripping of a thin oxidised surface that forms on the underlying fossil stratigraphic units. Bioturbation aids this erosion by loosening the stiff Pleistocene sediments and producing a thixotropic surface layer up to 5 cm thick. Periodic storms, waves or spring tides rework this loosened surface.

Cliff erosion.—Cliff erosion involves the retreat of coastline cliffs 1-2 m high and locally up to 6 m high. In plan the coast is typically scalloped. The seaward edge of mangal flats is the most common location for cliff erosion. The baffling effect of mangroves on tidal currents and the binding effect of

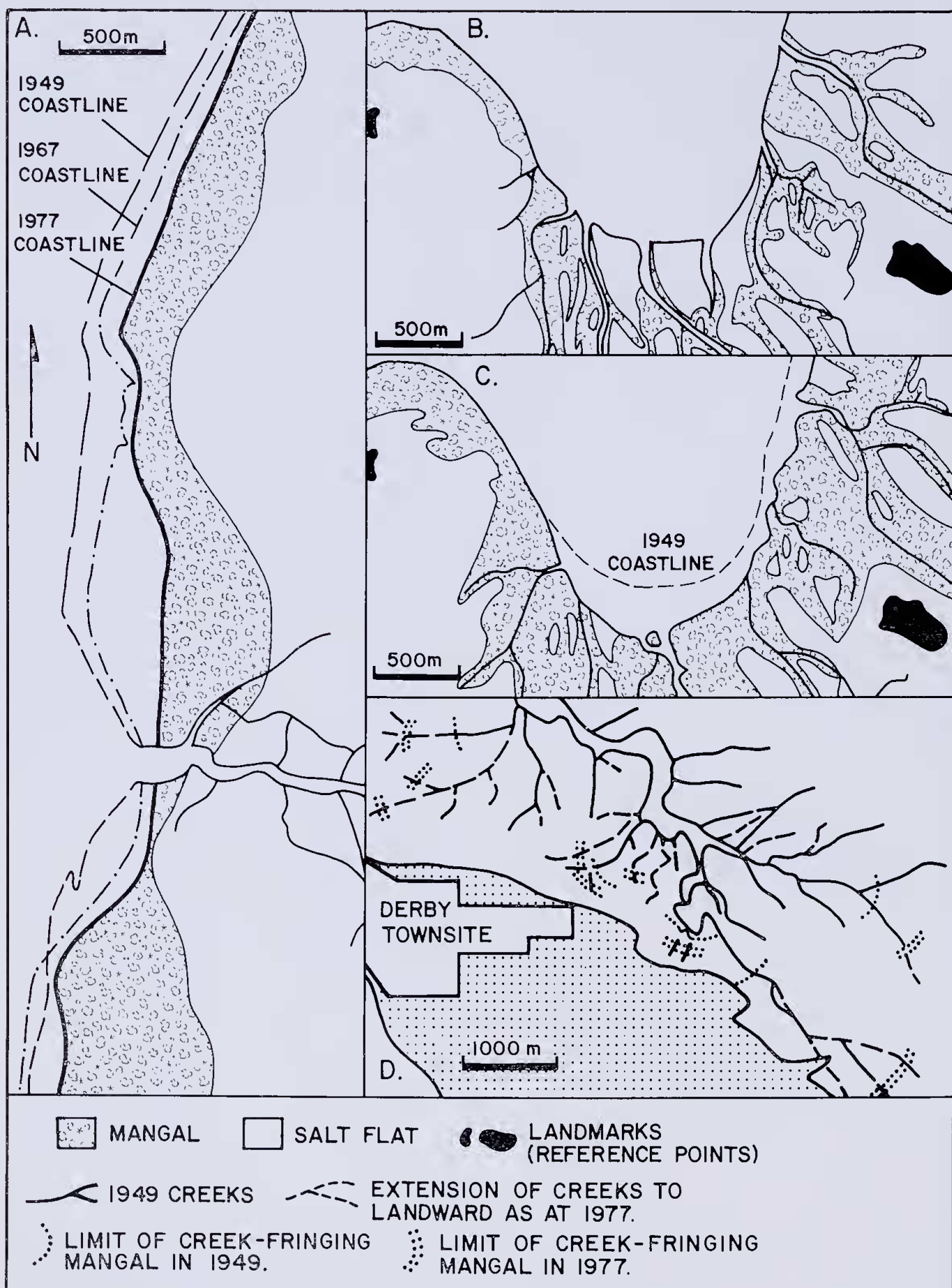


Figure 9.—Maps showing changes in coastline. A.—Southernmost portion of study area showing changes of coastline and erosion of mangal from 1949 to 1977. B and C.—Colac Shoals area showing retreat of coastline over the interval 1949 to 1977. Creeks have extended landward and mangal has encroached to landward along creeks and across salt flats. D.—Map centred on Derby peninsula showing headwater regions of Doctors Creek where the creek has extended headwaters to landward and creek-fringing mangals have followed.

their roots tends to make a marked distinction between the inclined-slope environment and the mangal flat and a sea cliff is formed most readily at their junction (Fig. 5C). Cliff erosion is caused by tidal scour, mass slumping and undercutting of mangrove root systems. Wave action during neap tides is also important because erosion can be localized at a standing water level during the high and low tide period. The rate of cliff retreat is dependent upon the stratigraphy of the coastline; cliffs cut into Doctors Creek Formation retreat faster than those cut into Pleistocene units.

Tidal-creek erosion.—Erosion by channels is termed tidal-creek erosion. Measurements in tidal creeks, intensely over 8 weeks, more generally over 4 years, and over 28 years from aerial photographs, show that they progressively deepen, widen and extend their headwaters to landward. Thus the gradation in creek size from small rut to large channel reflects stages of creek development. The small ruts a few centimetres deep at the headwaters of a tidal creek are initiated by mud cracks in the salt flat surface. The array of cracks between mud-crack polygons coupled with the slope of the tidal flat probably generates the meandering channel which, once it is formed, becomes entrenched. This meandering pattern remains with the creeks through all stages of their growth.

Within 10-20 years the small tidal ruts develop into small channels; these channels are only flooded during spring tides and are subject to sheet erosion typical of salt flats except that channelled ebbing tide waters are more erosive. Creeks continue to deepen and widen until the floor reaches a level below that of high water neap tide where sediment remains moist and waterlogged. A new process then operates; waterlogged banks frequently and repeatedly slump, resulting in a more rapid widening and deepening of the channels. The creek cross-section changes from a shallow V-shaped to a deeper U-shape.

Rates of erosion

Rates of erosion were variable from place to place, and at the same field station rates varied in time. The data presented below and in Table 3 give maximum rates of erosion. Erosion rates currently operating and those rates deduced from aerial photography (Fig. 11) indicate that qualitatively there are 3 rates related to foundation materials. The fastest rate occurs where there is erosion of Doctors Creek Formation. Moderate rates occur where there is erosion into Pleistocene formations. Slowest rates occur where there is erosion of hinterland dunes and bedrock.

Rates of sheet erosion.—Rates of degradation by sheet erosion were determined in areas A, D and I (Fig. 2). Erosion in area A indicates a loss of 30 cm of sediment within 10-15 years i.e. within the lifetime of mangroves whose roots are exposed. This gives a conservative estimate of erosion rate as 2-3 cm/year. Rate of erosion in area D was determined over 3 years and gave a value of 1-2 cm/year. A rate of approximately 1 cm/year has been determined in area I by levelling areas of salt flat which 28 years ago were supratidal grassy flats and now lie 30 cm below modern supratidal flats.

Rates of cliff erosion.—Rates of cliff erosion were determined by aerial photographic comparisons over a 28 year period and by direct measurement (Table 3). In southern parts of King Sound a fast retreat of 30-50 m/year has been estimated (areas K and L). Even faster rates of about 90 m/year occurred between 1949 and 1967 in the Alligator Creek area near the mouth of the Fitzroy River (Fig. 1). However, erosional rates of up to 2 m/year, which were directly measured (areas E and F), were more typical of most cliffs in the study area. Slow rates of 30 cm/year were determined from areas A and E.

This unequal rate of cliff erosion along a stretch of coastline typically results in a scalloped coast.

Table 3

Rates of erosion¹

Area ²	Type of erosion				
	Sheet	Cliff	Extension of creek headwaters	Channel widening	Channel deepening
A	2-3 cm/yr ³	0.3/yr ⁴	....	....	....
B	....	....	30-60 m/yr ⁴	3 m/yr ⁴	....
C	....	....	....	3-4 m/yr ⁴	....
D	1 cm/yr ⁴	....	....	0.3 m/yr ⁴	0.3-0.6 m/yr ⁴
E	....	0.3-2 m/yr ⁴	....	....	....
F	....	0.3-2 m/yr ⁴	....	2-4 m/yr ⁴	....
G	....	....	3 m/yr ⁴	....	0.06 m/yr ⁶
H	....	....	5-60 m/yr ⁵	....	....
I	1 cm/yr ⁵	....	0-3 m/yr ⁴	0.3-3 m/yr ⁴	....
J	....	....	10 m/yr ⁴	....	....
K	....	10 m/yr ⁴	30-100 m/yr ⁵	....	....
L	....	40-50 m/yr ⁵	15-17 m/yr ⁵	....	....
Alligator Creek	....	30 m/yr ⁵	....	....	....
	....	90 m/yr ⁵	....	....	....

¹ Maximum rates of erosion are rounded off to approximate values.
² Area location shown on Figure 2.
³ Estimated from inferred age of mangroves whose roots are exposed.
⁴ Direct measurement.
⁵ Determined from aerial photography over 28 years.
⁶ Measurement of depth against known age.

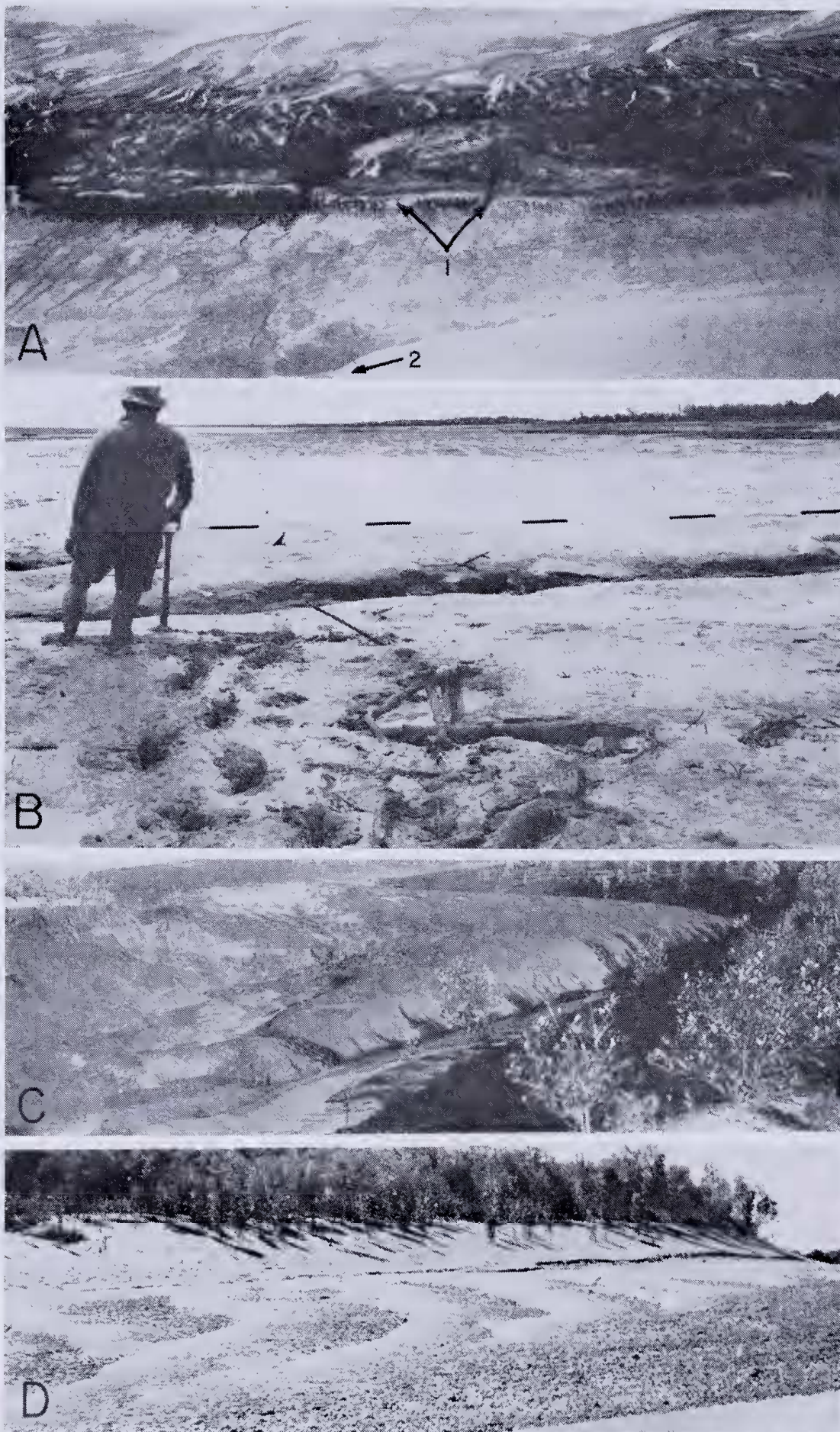


Figure 10.—Sites of sedimentation. A.—Aerial view showing a belt of mangrove (arrow 1) recolonizing a surface in front of a high tidal cliff. These mangroves have influenced deposition of mud. Once buried this cliff would appear as a scar within the mangal flat. Arrow 2 indicates sediment deposited at the mouth of a tidal creek. B.—Close-up of a creek-mouth deposit. Dashed line indicates the contact of the deposit (vener) on Pleistocene sediments. The creek deposit is composed of mud-pebble conglomerate, homogenous mud and mangrove debris. C.—Point bar of small creek showing (ephemeral) deposit of mud-pebble conglomerate. D.—Point bar deposit of large creek which has incised Pleistocene formations. The point bar consists of lithoclasts gravel with patchy veneer of megarippled sand.



Figure 11.—Carbonate nodules. A.—Platy nodules parallel to layering in upper Doctors Creek Formation under a salt flat; exposed by a tidal creek. B.—Platy nodules parallel to sedimentary layering exposed on wall of seacliff in front of mangroves. In foreground are nodules that have been reworked. Ruler for scale is 15 cm.

Rates of creek erosion.—The rate of creek headwater erosion, with ruts a few centimetres deep, directly measured was 3 m/year (area G). However, aerial photograph comparisons of deeper channels indicate that rates of 30-100 m/year for headwater erosion locally occur (areas G and I); more moderate rates determined by aerial photography were 5-10 m/year (area G). The rate of channel deepening has been estimated tentatively by measuring channel depths of creeks that have formed since 1949. A conservative estimate is that, on the salt marsh, centimetre-sized ruts develop into metre-sized creeks over a period of about 10-20 years. Direct data about the rate of channel deepening for established creek systems are lacking. However, the numerous exposures of young mangrove root systems as erosion removes the enclosing soil indicate that it can occur rapidly. For instance, some creeks 3-4 m deep have incised the flats after the establishment of a mangrove community that is at the most 10 years old. The mangrove roots hang exposed

across the creeks. Measured rates of channel widening range from 2-4 m/year and have been determined in areas B, C, D, F and H (Table 3).

Types of sedimentation

Sedimentation on tidal flats of King Sound in a regional context must be viewed as minor and the stratigraphic products transitory. The main sites of sedimentation are: (1) shoals, (2) sheltered embayments, (3) spits and cheniers, (4) mangal flats and (5) creek mouths and point bars.

The sediments range from coarse lithoclast and shell gravel through to sand, muddy sand and mud. Sediment types and their environmental location are summarised in Table 4. The various sources of sedimentary particles are summarised in Table 5.

Shoals.—Shoals are the most important of the depositional features within King Sound. Internally they are composed of the ideal shoaling stratigraphic sequence (Fig. 3G). Aerial photography and on-site

Table 4

Modern sediment types

Sediment	Structure	Fabric		Texture	Composition ¹	Locality	
Sand and shelly sand; locally lithoclastic sand	laminated to cross laminated	grainstone	....	medium and coarse sand; locally gravelly	quartz and skeletons; locally lithoclastic	low tidal sand flat, spits and cheniers, mid-channel shoals and point bars of large creeks
Lithoclast gravel; locally shelly	structureless to crudely laminated	grainstone	... ..	granules and pebbles some with sand interstitial to gravel frame	carbonate rock; locally shelly and with wood debris	low tidal gravel pavement; also at toe of sea cliffs cut into Pleistocene formations; point bars of large creeks
Mud-pebble conglomerate	structureless	....	packstone	....	pebbles and boulders with interstitial mud	toe of sea cliffs cut into Pleistocene and Holocene formations; point bars of small creeks; creek mouth deposits
Mud/sand laminite	....	bedded and laminated; cross-cutting burrows are common	grainstone to packstone in sand layers; mudstone in mud layers	medium to fine sand; silt and clay	quartz, skeletons, clay minerals, plant detritus	lower inclined slope
Mud laminite	laminated; commonly with burrows	mudstone	silt and clay in distinct laminae	quartz, skeletons, clay minerals, plant detritus	upper inclined slope
Bioturbated mud (locally shelly)	homogenous bioturbated locally laminated; in situ mangrove stumps	mudstone to packstone	....	silt and clay; locally with sand and gravel	clay minerals, quartz silt, skeletal silt, sand and gravel, wood, plant detritus lithoclasts	mangal flat
Laminated and vesicular mud	bedded to laminated; vesicular beds; rare to common burrows	mudstone	....	silt and clay; locally mud clasts	clay minerals, quartz silt, skeletal silt	salt flat

¹ See Table 5 for types of sediment particles.

Table 5

Types and sources of sediment particles

Sedimentary particle	Composition	Source				
		Fitzroy River input	Generated in basin	Eroded from older Holocene marine formations	Eroded from Pleistocene marine formations	Eroded from hinterland dunes and rock
Mud	Skeletal silt ¹	....	X	X	X	....
	Quartz silt	X	....	X	X	....
	Clay minerals	X	....	X	X	....
	Plant detritus	....	X	....	X	....
Sand	Skeletons ²	....	X	....	X	....
	Quartz	X	....	X	X	X
	Carbonate lithoclasts	....	....	X	X	....
	Other lithoclasts	....	....	....	....	X
	Plant detritus	....	X	X	X	....
Gravel	Shell ³	....	X	X	X	....
	Platy carbonate lithoclasts	....	....	X	X	....
	Granule-sized pedogenic nodules	....	....	....	X	....
	Plant debris	....	X	X	X	....

¹ foraminifer tests, spicules, mollusc fragments.² fragments of molluscs, echinoids, crustaceans, foraminifer tests, spicules.³ bivalves, gastropods, crustaceans.

observations show that large shoals develop proximal to rapidly retreating coasts where sediment input exceeds the rate of erosion at the site. Shoals themselves are subject to erosion and redistribution and in the long term they are transitory features. A series of shoals in the vicinity of Mary Island South for instance was completely eroded from above HWN to below MSL between 1949 and 1977.

Sheltered embayments.—Deposition takes place in sheltered embayments or backwaters where local eddies are developed in the main tidal flow. In these localities local progradation results in a complete or an incomplete ideal stratigraphic sequence as shown in Figure 3G. Again, in the context of net erosion along these coasts such deposits are transitory.

Spits and cheniers.—Spits and cheniers are accumulating along the northern half of the study area (Jennings and Coventry 1973). They have formed where the tips of longitudinal dunes are exposed to tidal erosion (Fig. 8) or (if shallowly veneered by Holocene deposits) periodically exposed to erosion (Semeniuk 1980). The sand is dispersed by long-shore tidal current both north and south from the eroded tip of a dune and is transported upslope by periodic storms. The sand progrades onto salt flats that occur in interdune depressions and also invades mangrove habitats.

Mangal flats.—Deposition locally occurs in front of sea cliffs where mangroves have recolonised a previously rapidly eroding coastline (Fig. 10A). Sediments probably accumulate due to mangrove effect of baffling, trapping and binding. Deposits built up during a mangrove colonising phase are severely cut back during the next erosional phase. Portions of the coast show scars of buried cliffs indicating they have undergone alternating erosion and deposition under such mangrove cover.

Creek deposits.—Sediments associated with creek deposits are thin (< 2 m) and generally ephemeral. Point-bar deposits, mid-channel shoals and creek-mouth fan deposits are the main accumulations (Fig. 10B, C and D).

Geomorphological development

Local geomorphology

Erosion is the dominant process on the tidal flats and therefore much of the geomorphology is directly related to it. However sedimentation also plays a minor part locally.

Sheet, cliff and creek erosion all occur to some extent everywhere on the tidal flats, but local geomorphology such as gradients, seacliffs and creeks, is largely dependent on which dominates. Broad, gently inclined surfaces are developed where sheet erosion is dominant, and scalloped coastlines with abrupt cliff lines occur where cliff erosion is dominant. Narrow, more steeply inclined surfaces are produced where sheet and cliff erosion alternate or where sheet erosion keeps pace with cliff erosion. Where sheet erosion occurs on flats adjoining creeks, then creek banks gently slope towards the channel. Cliff erosion that is parallel to the coast and concurrent with creek erosion results in abruptly terminating channels and hanging valleys. Cliff erosion parallel to creek margins is viewed as a type of rapid creek erosion and results in vertical banks.

The types of sedimentation that have influence on development of local geomorphology are (a) deposition of sediments in creeks (mouth fans, channel shoals, point bars) and (b) mangal flat deposits that bury seacliffs.

Geomorphic units

The various geomorphic units are formed mainly by erosional processes but they also reflect the availability of varying sedimentary particles. The vegetated dunes of the hinterland existed prior to the Holocene transgression (Jennings 1975; Semeniuk 1980) and so this geomorphic unit has not developed by tidal processes. Supratidal and saltmarsh flats develop by sheet wash of sediment off hinterland dunes onto tidal flats (producing aprons of muddy sand). Some supratidal and saltmarsh flats are erosional residuals of stranded high level Quaternary sediments that border the hinterland; these sediments are now undergoing erosion to levels of high water spring.

Most salt flats have formed by sheet erosion of high tidal and supratidal flats. Once a surface has been degraded to levels where there is periodic tidal inundation then physical, chemical and biological processes (desiccation, salt crystallization, gas bubbling, burrowing, periodic wetting) operate to develop the distinctive salt flat surface. Some salt flats associated with depositional tidal flats have formed by vertical accretion of tidal muds.

Mangal flats have formed where tidal flats have been degraded to levels at which mangroves can colonise (Semeniuk 1980) and inclined slopes develop where erosion has proceeded to the stage where the surface has been degraded to below mangrove level. In shoaling and prograding areas mangal flats and inclined slopes develop by sediment accretion.

Low tidal areas are composed of gravel pavements where erosion has exposed Pleistocene formations and a lag of carbonate nodules form at the surface. Sand flats form in low tidal areas where sand is available and is distributed as a sheet across tidal flats.

The other geomorphic units such as tidal creeks, seacliffs, spits and cheniers and rocky outcrops are the products of various types and/or stages of erosion and their origin is self evident.

Regional geomorphology

The regional geomorphology is dependent mainly on the extent to which erosion has incised coastal sedimentary sequences and on the type of foundation stratigraphy (Fig. 6). Depositional flats develop where sedimentation is dominant or where erosion/sedimentation is in equilibrium.

Unconformity flats with sea cliffs develop where erosion becomes accelerated and exposes Pleistocene units. Spit and chenier flats develop where erosion proceeds to the extent that salt flats are totally removed and the sea cliffs incise hinterland dunes. Further erosion ultimately exhumes bedrock and rocky shores are developed. Rapid erosion into Holocene deposits of the Doctors Creek Formation results in large amounts of reworked sediment that pile up into shoals, developing shoal flats. Finally where tidal creeks become abundant channelled flats are formed.

Sedimentation in localized sites within a net erosional framework has influence on development of regional geomorphology in the development of (a) shoals (shoal flats), (b) sheltered embayment deposits (depositional flats) and (c) spits and cheniers (spits and chenier flats).

Additional features

There are several additional features in the area that emphasise or reinforce the conclusions about erosion and sedimentation. When coupled with erosion rates (Table 3) these enable an extrapolation of erosion into the past. These features are: (a) nodules under the tidal flats, (b) dieback of grasses and pindan and (c) the imprint of (supratidal) vegetation roots on the stratigraphic sequence.

Carbonate nodules.—Nodules composed of Mg calcite, aragonite, dolomite, calcite or mixtures of these minerals occur imbedded in the Doctors Creek, Christine Point, Double Nob and Airport Creek Formations (Fig. 11). Generally there is a distinct association of nodule shape, nodule internal structure and chemical composition linked to host formation (Table 6).

The nodules occur at several stratigraphic levels and have formed in response to chemical alteration associated with unconformities or hypersaline groundwater fields (Table 6). All these types of nodules are being exposed and reworked by coastal erosion but those important to reconstruction of Holocene history are ones formed in hypersaline environments within Holocene formations under salt flats where groundwaters are carbonate-precipitating. An indication of how far erosion has incised the sedimentary formations is given by those nodules that are exhumed along the seacliffs in front of the mangrove belt (Fig. 11B); the nodules originally would

have formed under a salt flat at least several kilometres inland from the mangrove belt.

Dieback of grasses and pindan scrub.—Aerial photography shows that in past decades there were more extensive supratidal grassy plains and associated samphire flats. These have largely died back in response to sheet erosion that has lowered supratidal surfaces to levels of high water spring tide. On-ground inspection around residual grassy or samphire hummocks show that this dieback is continuing up to the present. Similar observations have been made on the seaward edge of the *Eucalyptus-Acacia* pindan scrub. At the junctions of the tidal flats where sheet erosion is proceeding at fast rates this terrestrial scrub is dying back and being replaced progressively by samphires and salt flat.

Imprint of vegetation roots on stratigraphic sequences.—Extensive areas of salt flats in the shallow subsurface (1-3 m) exhibit sediments that are riddled with fine rootlet structures. These root structures are unlike the coarse root structures forming under landward-fringe mangrove cover. The modern analogue for the fine rootlets is under supratidal grassy plains. Here sediment is desiccated mud, covered by a variety of annual and perennial grasses and samphires. Thus although hypersalinity has caused the supratidal grasses to die back and retreat, the former presence of the vegetation is indicated by their root structure.

Holocene tidal flat history

The synthesis of Holocene history of King Sound presented below revolves around 5 main points. These are: (a) alteration (diagenetic) overprints displaced from their environment, (b) erosion rates extrapolated into the past, (c) tidal flats in relation to large scale erosion, (d) origin of the Holocene Doctors Creek Formation and (e) ultimate sink for eroded materials.

Table 6

Features of carbonate nodules

Stratigraphic location	Shape	Size	Internal structure	Fabric relationship to host	Composition†	Inferred environment of precipitation	Comments
Upper parts of Doctors Creek Formation	platy to irregular	2-10 cm	structureless to internally laminated (inherent from host), unless replacing wood	replaces muddy sediment, mangrove wood, fossil crustaceans and sediment fill in <i>Teredo</i> borings	Mg calcite (aragonite and dolomite)	hypersaline groundwater	related to hypersaline diagenesis under salt flats*
Upper parts of Christine Point Clay	irregular	2-10 cm	structureless, unless replacing wood	replaces muddy sediment, mangrove wood, fossil crustaceans and sediment fill in <i>Teredo</i> borings	Mg calcite (aragonite and dolomite)	hypersaline groundwater	related to hypersaline diagenesis under salt flats*
Throughout Double Nob Formation	equant to spherical	1-10 mm	structureless	incorporates particles of the host	calcite	fresh water pedogenic	related to fresh water diagenesis associated with unconformity
Throughout Airport Creek Formation	platy concordant to layering in host	1-45 cm	internally laminated, inherent from host	cements the particles of the host	calcite	fresh water during sub-aerial exposure of host	

* See Table 1.

† brackets indicate that the mineral species is uncommon.

Alteration overprints displaced from their environment.—A study of the modern processes and biota on the tidal flat surface and subsurface shows that there is marked zonation of chemical and biological alteration features that correspond to specific tidal levels (supratidal, salt flat and mangal flat environments). It follows that an alteration feature if now found out of its environment will be a valuable tool in reconstructing Holocene geomorphic history. The main 2 imprints used in this study are nodules (indicative of hypersaline salt flat) and grass roots (indicative of supratidal flats). In King Sound these overprints in many localities are now out of their environment and indicate that (as coastal erosion proceeded) the geomorphic surface passed from supratidal with fresh groundwater, to salt flat with hypersaline groundwater, to the seacliff with oceanic groundwater. It also indicates that erosion has been a net event in the more recent Holocene.

Similarly as coastal retreat takes place mangroves encroach landward and alteration associated with mangrove environment overprints sediments that have passed through salt flat and supratidal flat alteration. The displaced alteration features indicate that at least several kilometres of coast have been lost in the Holocene. The maximum value is unknown but may be inferred by extrapolating rates of erosion into the past.

Extrapolation of erosion rates into the past.—The geomorphic, stratigraphic and diagenetic data suggest that erosion (and not coastal accretion) has also been a long-term event. The question then arises: for how long has erosion been operating? Mangrove wood has been dated by radiocarbon from various localities in southern King Sound (Jennings and Coventry 1973; Jennings 1975). Mangrove stumps under spits and cheniers dated at ca. 1000 yrs BP and younger showing that the Point Torment spits and cheniers were the last stratigraphic unit to be emplaced, confirming the stratigraphic evidence (Fig. 7 of Semeniuk 1980). However the Point Torment Sand is a unit developed by erosion of hinterland dunes and in essence represents the products of late phase erosion. Dates from the Doctors Creek Formation centre around 5000-6000 yrs BP showing that the bulk of that formation was rapidly deposited about middle Holocene. The formation is not accumulating today and stratigraphic and geomorphic data suggest it ceased deposition several thousand years ago. It is worthwhile then to explore the possibility that King Sound tidal flats have been eroding since 5000 yrs BP, the date about which the tidal flats ceased prograding. If the King Sound area earlier in the Holocene was a coastal plain then with erosion of both shores and leaving about 1 km for the Fitzroy Channel, there is: (a) only 2.5 km of shoreline erosion on each side of King Sound necessary to scour out the area alongside Alligator Creek, (b) 5-6 km of shoreline erosion necessary to scour out the embayment opposite Airport Creek, (c) 12 km of shoreline erosion is necessary opposite Christine Point and (d) 15 km of erosion is necessary opposite Point Torment.

The faster rates of cliff retreat (30-50 m/year up to 90 m/year) if they were consistent and if extrapolated back 5000 years give extraordinary widths (150-250 km) of coastline inferred to have been lost through erosion. This is far too excessive. More conservative rates of 30 cm/yr varying up to

2 m/y yield, over 5000 years of erosion, coastal loss of 1.5 km varying up to 10 km. It is obvious from these rates that the entire King Sound embayment potentially may have formed by large scale erosion and that this erosion is continuing to the present. The extrapolation of slow and moderate rates of sheet and tidal creek erosion leads to the same conclusion. Sheet erosion rates of 1 cm/year over 5000 years leads to a lowering of tidal flats by 50 m. This figure again seems excessive and very conservative rates of tidal flat degradation appear to be well capable of eroding large tracts of tidal flat. Tidal creek channel widening is a more important rate to extrapolate than deepening and lengthening of creeks. Tidal creek widening at a rate of 2-4 m/yr means that a creek 1 km wide (such as Doctors Creek) may form in 250-500 years. If the larger channel between Mary Island and the mainland (Fig. 1) represents a widened creek than it could have formed in 1500-3500 years.

The results are clear that, given present rates of erosion, it is conceivable that King Sound has formed by erosion of more extensive tidal flats.

Tidal flats in relation to the inferred large-scale erosion.—The 6 tidal-flat types (Fig. 6) are interpreted to represent stages in the large-scale erosion of tidal flats and hinterland. Depositional flats represent equilibrium or depositional conditions. Unconformity flats represent net erosion situations where Pleistocene formations are exposed. Spit and chenier flats and rocky shores represent situations where erosion has trimmed back the extensive tidal flats until it is incising the hinterland of dunes and bedrock. Channelled flats represent situations where tidal flats are thoroughly incised by tidal creeks.

If this thesis is correct then herein lies an explanation for the variation south to north along King Sound shores. Large-scale erosion would have commenced in northern parts and progressed south such that it largely completed removal of tidal flat material in northern areas (spit and chenier flats) and is in process of removing them in south areas (the extensive flats south of Derby).

Origin of the Doctors Creek Formation.—If erosion is the net process today and has continued for the last several thousand years, how did the Doctors Creek Formation originate? The lithology and stratigraphic sequence within the formation show that it formed by a combination of lateral progradation and vertical shoaling (Semeniuk 1981). The similarity of sediment types, sedimentary structures, biogenic structures, fauna and flora in the formation with modern equivalents is direct. However, apart from local sheltered embayment accumulations and shoal areas the bulk of the Doctors Creek Formation is largely eroding.

This anomaly may be explained by viewing the modern tidal flat in a regional context of sedimentary budget. The Fitzroy River, the ultimate source of sediments for King Sound flows for only 3-4 months of the year (Public Works Department 1976). During this time flow rates are not sufficient to mobilise sediments for the full 3 months. River flow is intermittent although instantaneous flow may reach 5000 m³/sec. Therefore it appears that the estuarine and tidal environment of King Sound receives sediment for less than 3 months from the river but

undergoes semidiurnal tidal erosion for the remainder of the year. Clearly, today the sediment input is insufficient to counter erosion.

For the Doctors Creek Formation to accumulate there needs to be a sufficient sediment supply. A larger and more continuous river input would provide this so that sedimentation can overwhelm erosion. However this suggests a more humid climate with a longer and more intense wet season. The implication of this conclusion is clear. The stratigraphy/erosion/sedimentation history points to a climatic change from humid to semi-arid during the Holocene. As the climate became more arid, less rainfall resulted in less river (and sediment) input and the balance between sedimentation/erosion was tipped toward erosion which is the dominant process today. Erosion since then has been stripping and redistributing sediments deposited earlier in the Holocene and sediments of pre-existing Pleistocene formations.

Ultimate sink for eroded materials.—The bulk of the tidal-flat sections consists of mud (upper Doctors Creek Formation, the entire Christine Point Clay and major portions of the Airport Creek Formation). Erosion of mud results in the turbid waters of King Sound. These turbid waters extend out of King Sound and deposition of mud probably takes place in deep water offshore. Thus there would be a net removal of mud from the King Sound embayment. This would account for the loss of most of the sedimentary section.

Sand however is not so easily mobilised. Much of it forms the lower stratigraphic unit of the Doctors Creek Formation and as erosion proceeds it is left as a residual sheet that is being dispersed continually across King Sound. Erosion of King Sound shores taken to completion thus would result in spit and chenier flats and rocky shores bordering the hinterland and the interior of King Sound would be underlain by a vast residual sheet of sand and lithoclast gravel.

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